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THESIS

A SIMULATION STUDY OF ACOUSTIC VARIABILITY DUE TO INTERNAL SOLITARY WAVES ON THE MID-ATLANTIC CONTINENTAL SHELF

by

Seng-Leong Ng

March, 1997

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Thesis Co-Advisor: Kevin B. Smith

Thesis
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During the summer of 1995, a multi-institutional field study called Shallow-Water Acoustic Random Medium (SWARM) was conducted in the Mid-Atlantic Bight continental shelf region off the coast of New Jersey. Environmental and acoustic sensors were deployed as part of SWARM to measure and characterize the internal waves and their impact on the spatial and temporal coherence of the acoustic transmissions. As part of the environmental monitoring network, two bottom-moored, upward-looking acoustic Doppler current profilers (ADCPs) were deployed. Large-amplitude, non-linear, internal soliton wave packets were observed to propagate shoreward from the shelfbreak. Based on the ADCP observations, a kinematic model of the soliton wave packets was developed to synthesize the corresponding temporal and spatial fluctuations in the sound-speed field. Using a coupled normal-mode sound propagation model and the synthesized sound speed variations, the variability of sound pressure and of the modal amplitudes for a 224 Hz CW transmission were simulated. The auto and cross-correlations of sound pressure at different depths, and of the modal amplitudes at a fixed range, were computed in an effort to estimate the vertical and temporal scales of the fluctuating sound field. The simulation method, the simulated acoustic variability as well as the results of the correlation analysis are presented and discussed in this report.

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A SIMULATION STUDY OF ACOUSTIC VARIABILITY DUE TO INTERNAL SOLITARY WAVES ON THE MID-ATLANTIC CONTINENTAL SHELF

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ABSTRACT

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I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

Isolated nonlinear waves of great durability were first reported propagating in a shallow, unstratified Scottish canal by J. Scott Russell (1838), but a theoretical explanation was not offered until D. J. Kortewed and G. de Vries published in 1895, explaining them mathematically as solitary waves of unchanged shape. The word 'soliton' was coined by Zabusky and Kruskal (1965) after 'photon', 'proton', etc. to emphasize that a soliton is a localized entity which may keep its identity after an interaction. The Greek word 'on' means solitary. Recognition of the nonlinear and, consequentially, the solitary character of oceanic internal waves in continental shelf waters appears to have first been made in the early 1970s (Ziegenbein, 1960, 1970; Lee and Beardsley, 1974), and extensive investigations into the soliton characteristics have since been made by several groups of researchers. A good summary of the various investigations can be found in Apel et al. (1985).

Although several oceangraphic studies have been carried out to describe and characterize the dynamics of solitary internal waves on the shelf, the investigation of the effects of these waves on sound transmission is still far and few in between. Large amplitude internal solitary waves can result in large variability of sound speed as they propagate through the medium. These abrupt changes in the sound speed structure can have great impact on the performance of a sonar system deployed in a shallow water shelf environment. To understand the potential impacts of the internal solitary waves on sonar system performance and/or help in the design of future systems that will minimize such impacts, it is necessary to quantify and characterize the induced acoustic variability. For example, the estimations of parameters such as the de-correlation time and lengths of the sound field will provide important design information for optimizing integration time and aperture size.

The joint acoustic-oceanographic field study called Shallow-Water Acoustic Random Medium (SWARM '95), conducted over the Mid-Atlantic Bight continental shelf region off the coast of New Jersey, has captured a comprehensive data set that will allow for the qualification and characterization of the acoustic properties (SWARM Group, 1997). The purpose of the thesis work reported here is to simulate initial estimates of these space and time scales in the fluctuating sound field using oceanographic observations from SWARM '95 in conjunction with a state-of-the-art sound propagation model.

B. SWARM '95

Under the sponsorship of the Office of Naval Research (ONR), SWARM '95 took place during 20 July to 12 August 1995 in the Mid-Atlantic Bight continental shelf region off the coast of New Jersey (see Figure 1). The primary objective of this experiment was to quantify the interaction of 10-2000 Hz acoustic signals with shallow water linear and non-linear internal waves. In order to accomplish this objective, very high quality physical oceanographic data and bottom geoacoustic data were collected along with acoustic transmission data. In addition to supporting the acoustic measurements, the oceanographic data were of sufficient quality to support studies of generation, propagation and dissipation of the internal waves within the shelf region.

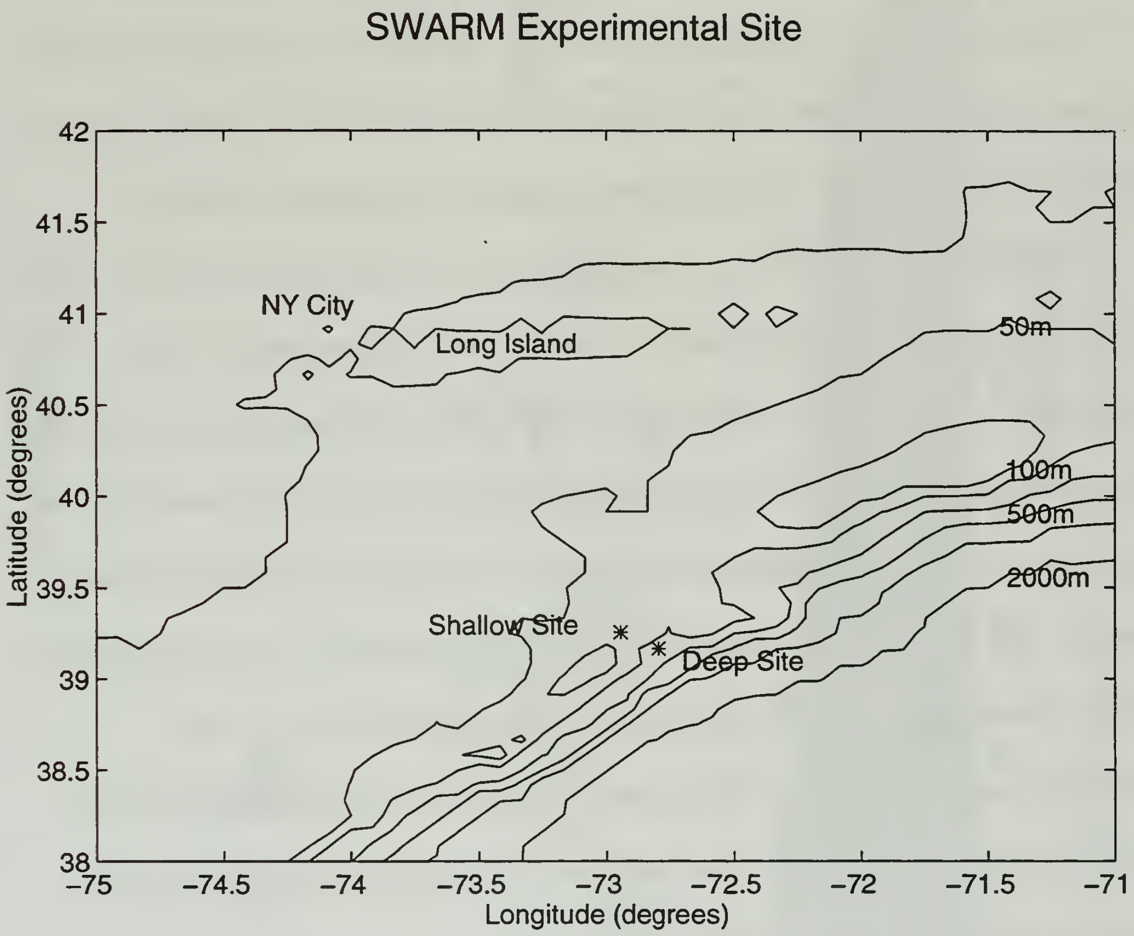

Figure 1. Locations of the two Naval Postgratuate School ADCPs in Swarm '95 along with the bathymetry of the region. The ADCP locations are labeled as Shallow Site and Deep Site respectively.

SWARM '95 was a large, multi-institution, multi-investigator project. Investigators from the Naval Research Laboratories (NRL), Woods Hole Oceanographic Institution (WHOI), University of Delaware, and the Applied Physics Laboratory of Johns Hopkins University (APL/JHU) participated directly in the cruise. Investigators from Naval Postgraduate School (NPS), University of Rhode Island (URI), Scripps Institute of Oceanography (SIO), University of Miami, and Northeastern University contributed equipment and/or participated in the analysis. NPS contributed two Acoustic Doppler Current Profilers (ADCPs) and subsequently analyzed the measured time-series.

The collection of the acoustic and oceanographic data during SWARM '95 involved three research vessels working at the experimental site, two of which occupied the site for the full duration of SWARM. The collection included successful deployment and recovery of twenty-five oceanographic and/or acoustic moorings. A representation of the environmental and acoustic data collection efforts is provided in Figure 2. The environmental measurements included those from: two bottom-moored ADCPs, thermistor chains, expendable bathythermographs (XBTs), a towed conductivity temperature depth (CTD) sensor, CTD casts, a vessel-mounted ADCP along with imagery from spaceborne and airborne Synthetic Aperture Radar (SAR) systems and shipborne radar imagery.

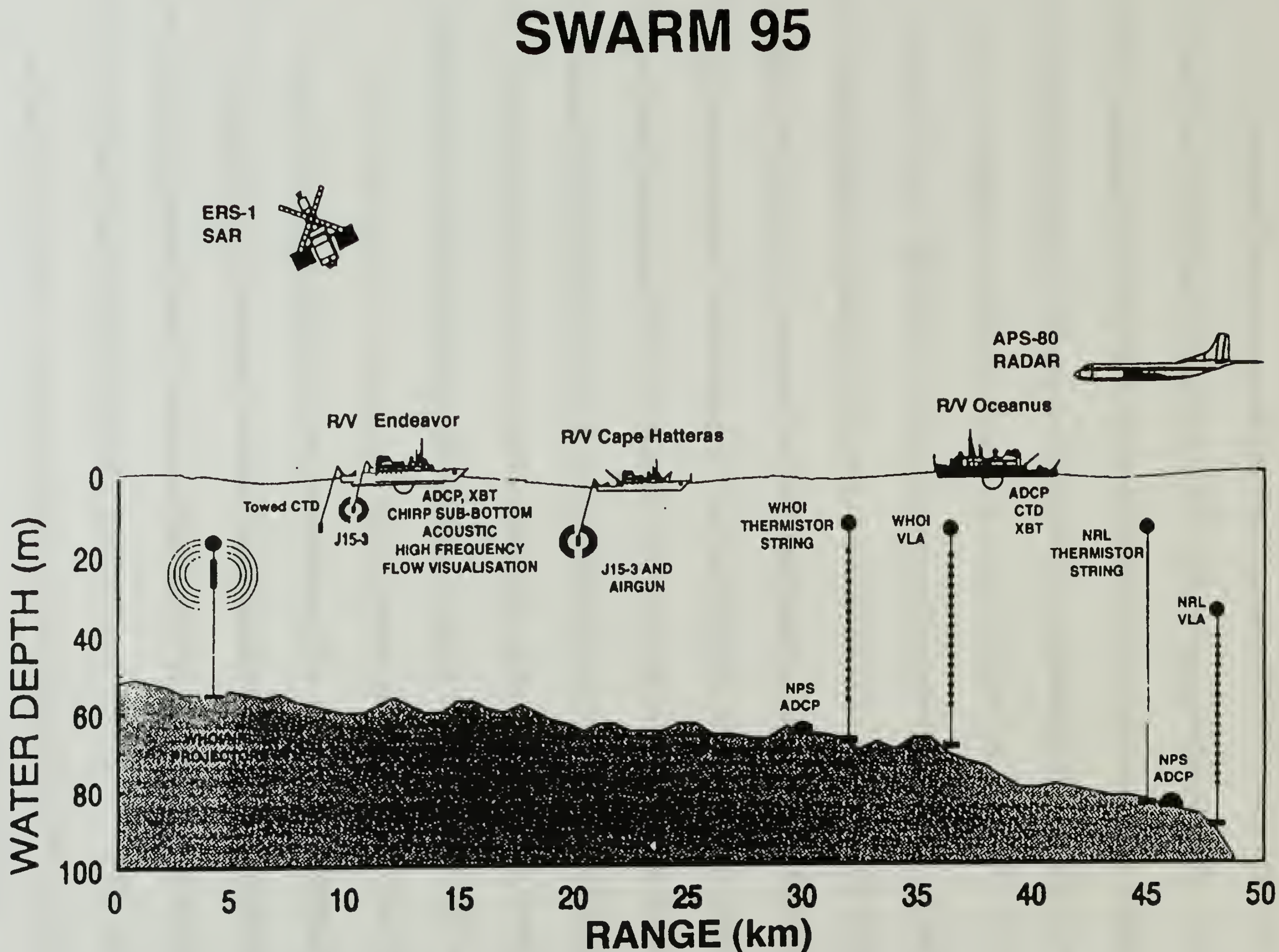

Figure 2. A schematic measurement assets involved with data collection during SWARM '95.

C. A REVIEW OF PAST ANALYSIS

1. SWARM Oceanographic Results

As part of the SWARM environmental monitoring network, two RD Instruments (RDI) Self-Contained Acoustic Doppler Current Profilers (SC-ADCPs) were moored 4 m above the seafloor, facing upward, at two separate locations, 16.5 km apart, along the experimental track. While one of them was placed in 103 m of water at 39° 10.000`N, 72° 47.416`W near the shelf-break (hereafter referred to as the "Deep Site"), the other one was in 75 m of water at 39° 25.33369` N,72° 56.5942`W ("Shallow Site" hereafter). Each ADCP was configured to transmit 225 pings per ensemble, with an ensemble sampling interval of 90 seconds. The acoustic frequency for the pings was 307.2 kHz. The four upward projected beams were oriented thirty degrees from the vertical and the data were recorded in earth coordinates (north, east and up each being positive). Each ADCP had a 4 m sampling blank directly above the transmitter head, then it sensed the water column in 4 m long depth bins. With these settings of profiling parameters, the current velocity measurements were accurate to approximately 1 cm/s. Measurements at the Shallow Site were collected in 16 depth bins centered from 67 m to 7 m below the surface. At the Deep site, the data was obtained in 22 depth bins centered from 95 m to 11 m below the sea surface. Thus, the resultant ADCP data set comprises time series of depth profiles of three-dimensional current velocities with a sampling time interval of 90 s and a depth interval of 4 m. While the Deep-Site time series encompasses data from Julian date (JD) 204 to JD 221, the Shallow-Site time series is 4 days shorter, containing data between JD 209 and JD 222.

The detailed time-series analysis of the data collected by the two Acoustic Doppler Current Profilers (ADCPs) have enabled the SWARM Group (1977) to establish many important findings of the soliton packets over the Mid-Atlantic Bight continental shelf region off the coast of New Jersey. Some significant results are:

a. Generation mechanism: The data showed that the generation mechanism is highly consistent with the lee-wave hypothesis requiring steady offshore flow to induce depressions in the pycnocline directly offshore from the shelfbreak. The lee wave is eventually released from its phase locked position when the flow reverses and propagates up the shelf as soliton wave packets. Steady offshore flow provided by the ebbing barotropic tide can be nullified by synoptic shoreward currents. When this takes place, the production of soliton packets is totally suppressed. This suppression was observed during the passage of a storm event in SWARM '95.

b. Generation sites: There are multiple soliton generation sites at the vicinity of SWARM's area of investigation which produced interfering wave packets as they propagate shoreward. Localization of these sites is possible through further analysis in conjunction with SAR data.

c. Propagation characteristics: Only the propagation characteristics of the leading soliton can be described by weakly nonlinear soliton theory, i.e., the Kortewed-de Vries (KdV) equation. A more sophisticated dynamical model is required to emulate the evolution of the entire wave packet.

d. Spectral characteristics: The spectral characteristics of the internal-wave field is temporally non-stationary and spatially inhomogeneous, with significant differences between periods with and without soliton activities.

2. Dissipation and Shoaling Effects on Soliton

The KdV internal solitary wave theory has been extended to include dissipation and shoaling effects by Liu (1988). In his investigation of internal solitory wave packets using numerical solutions, Liu showed that without the dissipation and shoaling effects included, each individual depression retains its shape and propagates independently with a phase speed which is linearly proportional to its magnitude, and thus the rank-ordered individual depressions separate further apart as time progresses. When dissipation and shoaling effects were included, however, the numerical solution revealed that the relative balance of dissipation and shoaling effects is crucial to the detailed evolution and structure of the wave packet. These effects are in fact required to keep the rank-ordered individual depressions to stay together in a packet instead of moving away from each other.

The various numerical solutions presented by Liu in his paper also showed that the entire soliton wave packet approximately retains its shape and moves at a uniform speed over short durations of about 30 minutes. This approximation of a uniform-speed, form-preserving wave packet over a 30-minute time scale was used in this thesis research to simplify the modeling of the evolution of the wave packet, and hence the associated sound-speed perturbations. This approximation, of course, is only valid if the acoustic de-correlation time is much shorter than 30 minutes.

3. **Linear waves**

It is theoretically possible for linear waves to form spatially decaying oscillating tails that follows the nonlinear solitons in the packet. The ADCP data collected by the SWARM Group (1997) also showed that such oscillating tails may indeed exist.

Yih (1979) published that an internal solitary wave of a certain mode is supercritical with respect to the corresponding linear long wave speed, which is the maximum phase speed of all linear periodic waves of this mode. Therefore, it is expected that small amplitude waves associated with the same mode as a KdV solitary wave cannot form oscillatory tails. However, Yih also pointed out that both the phase speed of linear waves of a certain wavenumber and the nonlinear phase speed of a soliton decreases as the mode number increases, implying that for a solitary wave of mode higher than the first, there exist lower-mode linear short waves that can move with the same phase speed. This suggests that a KdV solitary wave in a mode higher than the first can develop oscillations at its tails owing to lower mode short waves. In the course of their investigation of internal wave disturbances, generated by stratified flow over a sill, Farmer & Smith (1980) observed mode-2 'solitary-like' waves followed by a train of smaller-amplitude mode-1 short waves, in qualitative agreement with the theoretical prediction.

The oscillatory linear waves were not considered separately in this investigation. They would be empirically modeled as part of the wave packet if they were presented in SWARM.

D. THESIS OBJECTIVES AND APPROACH

Though many investigations have been conducted to observe internal soliton packets and to establish the theory to describe their dynamics, studies on their effects on sound transmission have been minimal. Studies on the effects of soliton wave packet on the temporal and vertical structures of the sound field are thus the focus of this paper.

The objectives of this thesis are:

1. To synthesize the temporal and spatial structures of the sound filed for a 224-Hz CW transmission using the processed ADCP data from the SWARM '95 experiment;

2. To estimate the de-correlation time and vertical de-correlation lengths of the fluctuating sound pressure and the de-correlation times of the modal amplitudes for the same 224 Hz transmission at 10 km away from the sound source with a simulated vertical line array.

The ADCP data collected from SWARM were used to model the perturbations of the sound speed field. The changing sound speed field was then used as input to the coupled normal-mode model of Chiu et al. (1996) to calculate sound pressure as well as the modal amplitudes at a frequency of 224 Hz. The acoustic de-correlation times and lengths are finally estimated from these synthetic time series of sound pressure and modal amplitudes.

E. THESIS OUTLINE

The remainder of this thesis consists of three chapters. Chapter II discuss the modeling of the soliton wave packet and the coupled normal-mode model of Chiu et al (1996). In Chapter III, the simulation results of the space-time variability of the transmission loss and modal amplitudes are presented. Also discussed is the analysis of de-correlation times and vertical lengths of sound pressure and the de-correlation times of modal amplitudes. Chapter IV presents the conclusions of this thesis.

II. ACOUSTIC MODELING

A. SOLITON WAVE PACKET

Observed soliton packets in SWARM '95, as shown in figure 3, were used to empirically model the sound-speed perturbations. The segment shown, spanning from Julian day 211.3 to Julian day 213.3, corresponds to the displacements of the first baroclinic ocean modes derived from the ADCP current data using an empirical orthogonal decomposition and the nonlinear relation between current and displacement

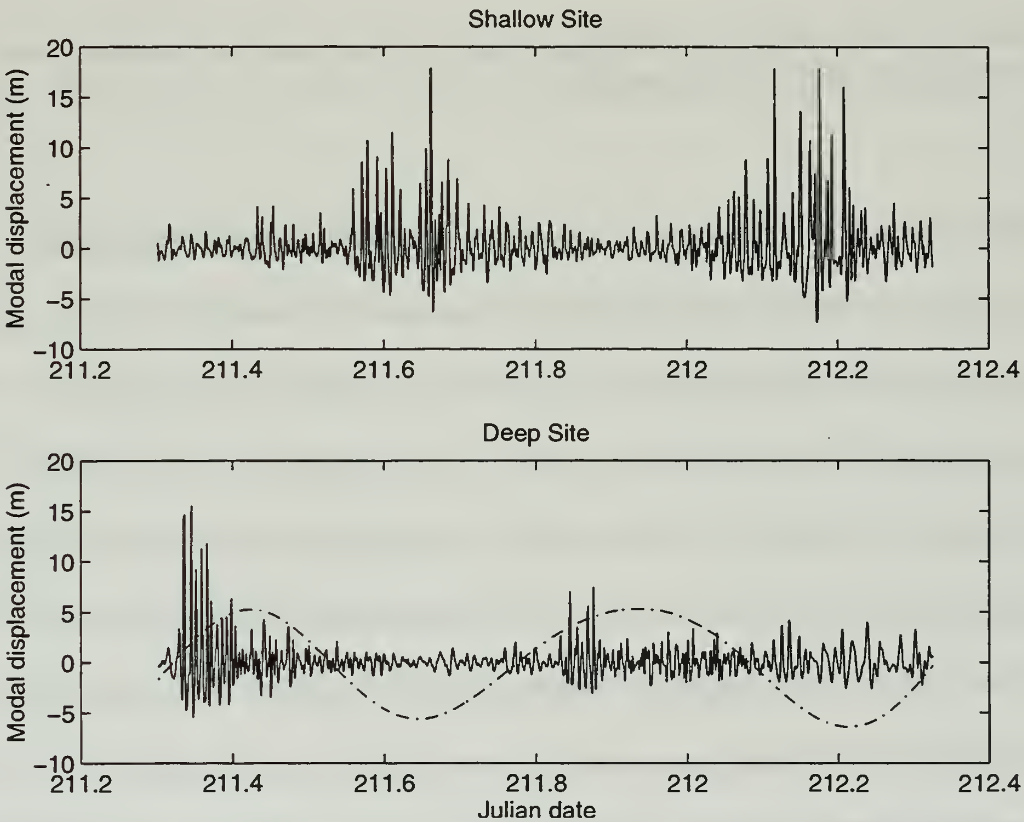

Figure 3. A segment of highpass time-series of modal displacements, at the Shallow (top) and Deep (bottom) Sites. The upslope barotropic tidal current (dot-dashed line in units of cm/s) is superimposed to show that this segment encompasses two tidal cycles with strong soliton packets generated near the Deep Site during the tidal flood.

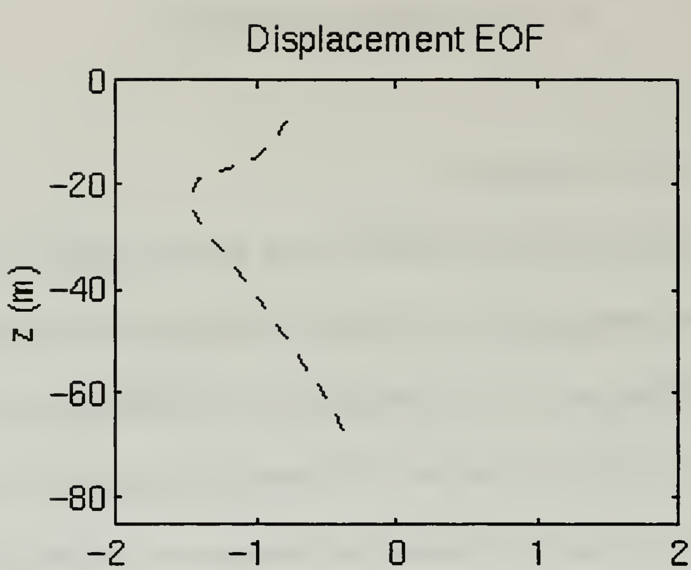

Figure 4. Vertical structure of displacement. The first vertical empirical orthogonal mode derived from the ADCP data is shown.

(SWARM Group, 1997). The vertical structure of the first baraclinic displacement modes is shown in figure 4. Note that only the dominant first baroclinic mode is used to synthesize sound-speed perturbation. Using the front portion of the segment displayed in figure 3 for the Deep Site, an observed average phase speed of 0.8333 m/s, and the approximation of a uniform-speed, form-preserving packet over short time scales, the corresponding spatial structure of the soliton modal displacement was extrapolated. The length of the soliton packet covers a distance of 10 km within which the temporal and vertical structure of the sound field was subsequently synthesized and examined. In figure 5, a "snap-shot" of the spatial structure of the packet is displayed, showing its modal displacement at a time referenced to zero second and distances relative to the sound source in the simulation.

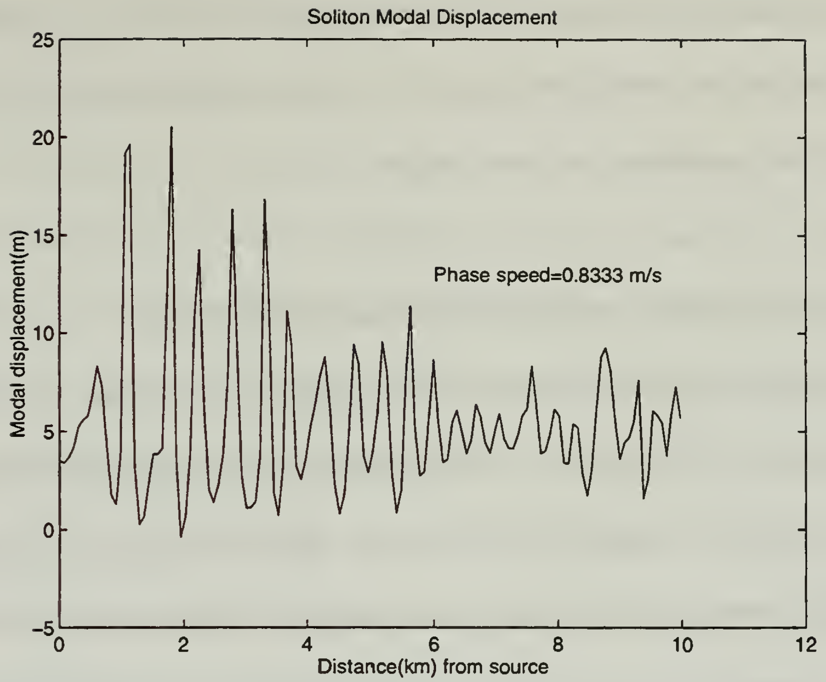

Figure 5. Spatial structure of soliton modal displacement from the sound source at t=0..

To synthesize the fluctuating sound field using the coupled normal-mode model, a 224-Hz CW sound source at a depth of 50 m was simulated. A uniform water depth of about 80 m was simulated. At the initial time, i.e., t=0, the source was at the leading edge of the soliton packet. The movement of the packet was simulated by translating the entire wave packet with a phase speed of 0.8333 m/s. "Snap-shots" of the soliton wave packet were taken at every 5 seconds to create the sound speed perturbations at those instances. The sound speed perturbations are simply the products of the displacements and the vertical sound speed gradients of the mean profile. This mean profile is shown in Fig 6. With such an evolution model of the sound speeds, the fluctuating acoustic wavefield within a range of 10 km from the sound source was then calculated at a geophysical time-step of 5 seconds over a period of half an hour by the coupled normal-mode model of Chiu et al. (1996). This thus produced the time series of sound pressure at various ranges and depths as well as time series modal amplitudes at various ranges.

B. COUPLED NORMAL-MODE PROPAGATION MODEL

The description of acoustic propagation via coupled normal-mode theory was proposed independently in the papers written by Pierce(1965) and Milder(1969). The mathematical formalism of coupled mode theory was described in these two papers though both authors were more concerned with situations in which the mode coupling process could be ignored.

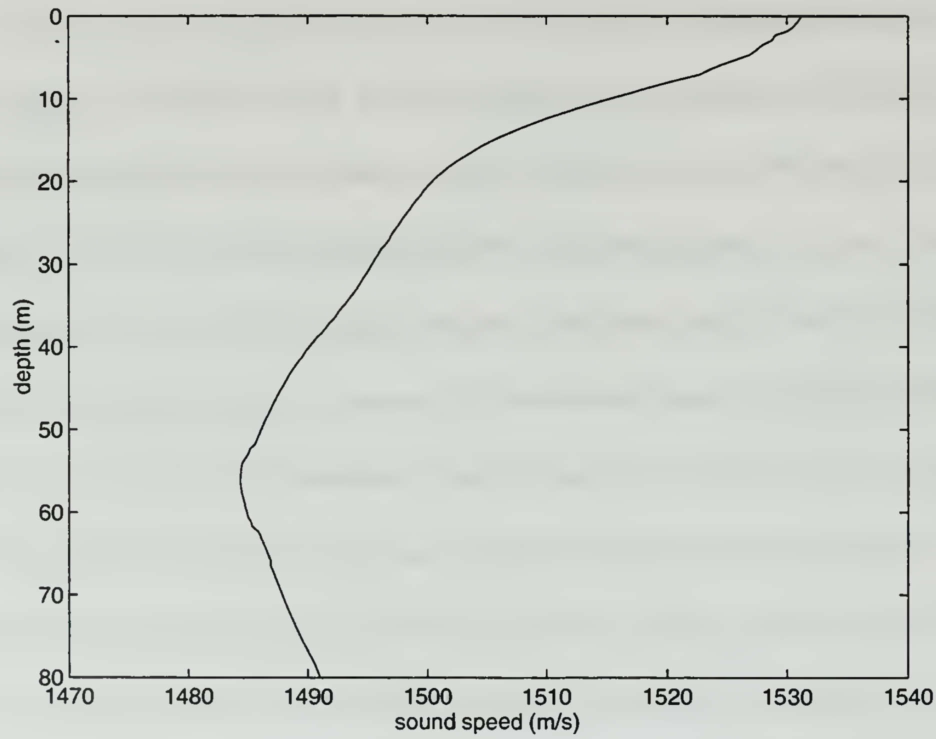

Figure 6. The mean sound-speed profile.

Chiu et al. (1995 and 1996) presented the three and two dimensional formulations of their coupled-mode model approach in the two separate papers. The medium was treated as a waveguide bounded by a flat, pressure-release surface and a flat, rigid basement. Within the waveguide, sound speed c, density ρ, and attenuation rate α were allowed to be arbitrary functions of range, depth and azimuth including discontinuities. These discontinuities define the locations of the generally variable water-sediment and sediment-sediment interfaces.

The complete derivations of the couple-mode modeling approach and a two-dimensional numerical implementation can be found in Chiu et al. (1996). The MATLAB code generated based on the modeling approach detailed in the paper was used to calculate the fluctuating acoustic wavefield in the presence of the evolving soliton wave packet.

III. RESULTS AND DISCUSSIONS

A. ACOUSTIC VARIABILITY

Figure 7 shows the temporally and spatially varying transmission loss (TL) calculated by the coupled normal-mode model. Only the TL at every 90 seconds is displayed although it was calculated at a 5-second interval.

Given the large displacements produced by the soliton packet, the large fluctuations in the calculated transmission loss are expected. According to Taube (1996), hydrographic measurements obtained during SWARM '95 indicated that the temperature gradients are as large as 0.7°C/m at the thermocline, implying that a 10-m internal wave can cause a 7°C temperature change and a 15-m wave can produce temperature fluctuations as much as 10.5°C. Such large fluctuations are often seen in the SWARM '95 thermistor-chain records during the passage of soliton wave packets.

Although loss of slightly more than 50 dB after the first 0.5 km due to near-field spherical spreading is shown consistently in all the time intervals. At longer distances, there are rampant abrupt variations in the TL of up to 20 dB over a short range of 50-100 m out to the 10 km range. These spatial changes, i.e., highs and lows, are due to the interference of the different normal modes. Of interest is the shifting of the locations of the highs and lows in the TL as the soliton wave packet evolves in time. These shifts, or changes in the interference pattern, are due to small but different changes in the phases of the different normal modes. These shifts result in a temporal variability in the TL that has a time scale of approximately 10 minutes as displayed in Figure 7.

To demonstrate the importance of mode coupling, the calculated magnitudes of the first five modes versus range at a given time are shown in the bottom panel of Figure 8. The corresponding modal displacement for the same time interval is shown on the top. Energy transfer between modes is evidence. For example, modes 1 and 2 as well as modes 3 and 5 are easily seen to be tightly coupled. As energy in one mode increases, the energy in the other mode decreases. It can be seen that mode coupling takes place after the leading edge of the soliton wave packet. When the displacement is small, like before and after the leading portion of the wave packet, the coupling between modes is not significant. Active energy exchange between modes, thus largely occurs within the front portion of the packet. It is also noted that active mode coupling usually takes place at or near the peak locations of the individual depressions where the fluctuations are large. This is again readily evident in the coupling of modes 1 and 2 and modes 3 and 5.

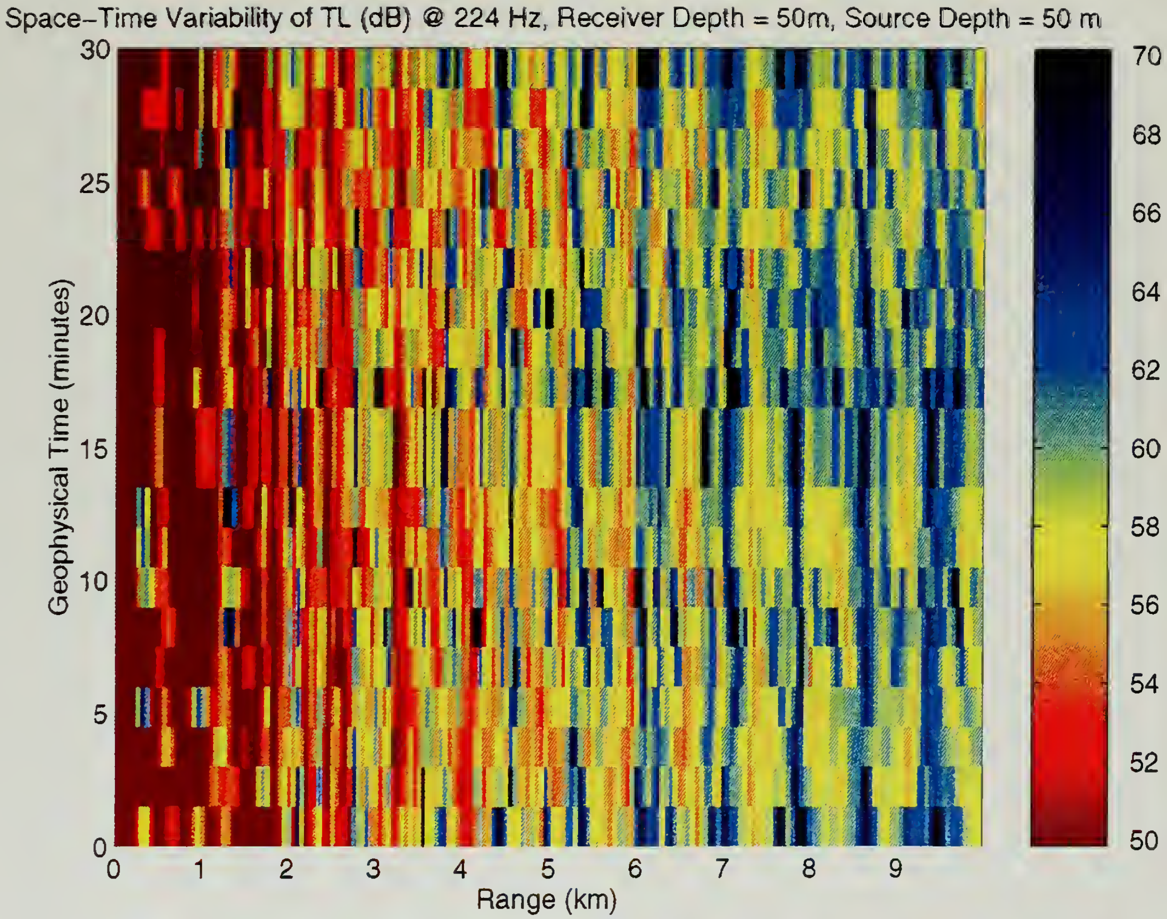

Figure 7. Space-time variability of transmission loss.

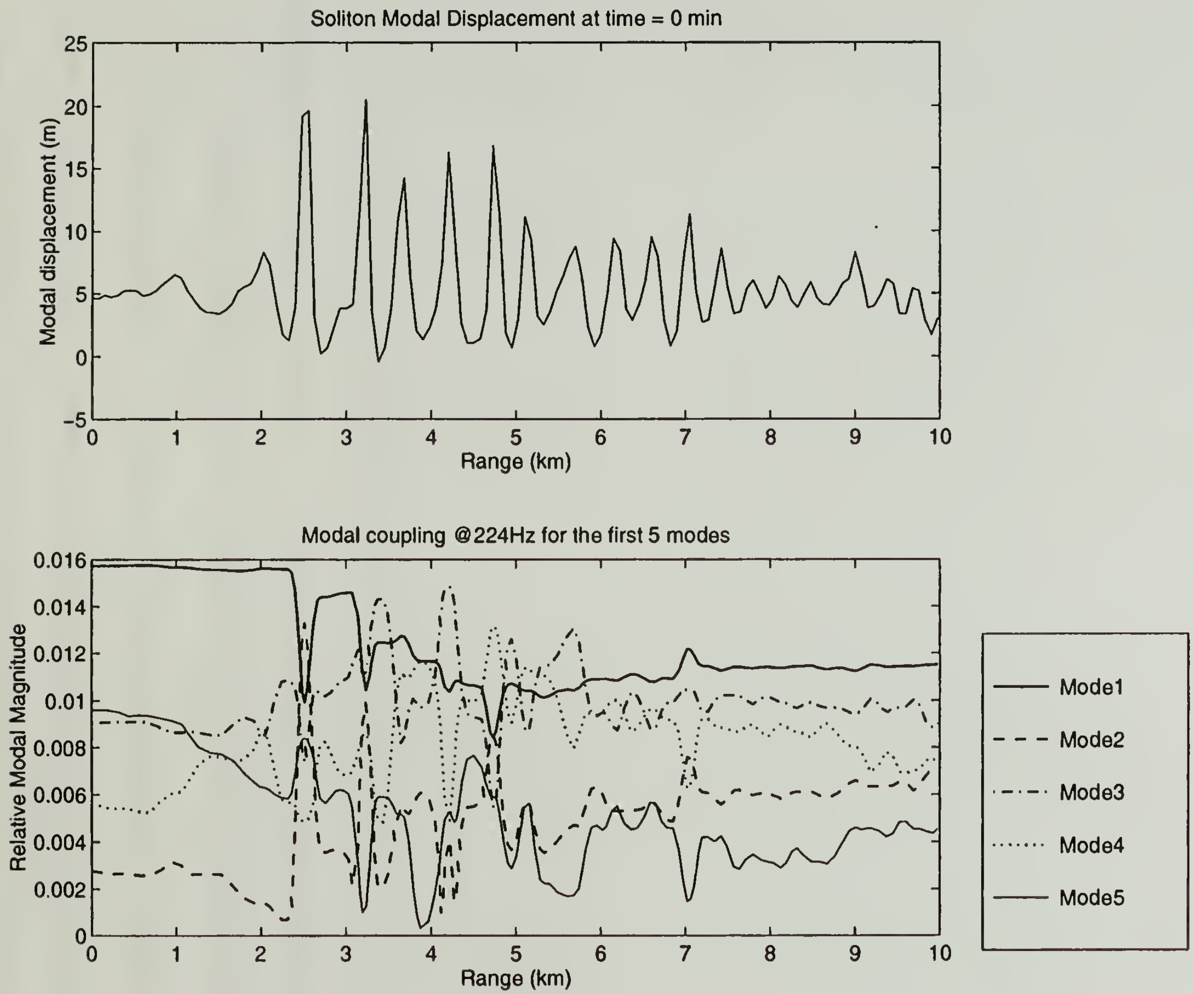

Figure 8. Soliton modal displacement (top) and the relative modal magnitudes of the first 5 acoustic normal modes (bottom). Note that a positive modal displacement implies a depression since the vertical function of the first baroclinic mode is normalized to have negative values.

Figure 9 shows a pseudocolor color plot of the variability of the relative magnitude of mode 1 and mode 2 over the entire modeled duration of 30 minutes. It is observed that the mode magnitudes change abruptly at the leading edge of the soliton packet as it propagates toward the sound source. Active coupling of modes 1 and 2 takes place immediately after that. Once again, it is observed that large coupling only occurs within the front portion of the wave packet where the perturbations are large. At the downstream of the packet the coupling of the acoustic energy lessens. The variability in the modal amplitude are of the same order as the TL which is about 10 minutes.

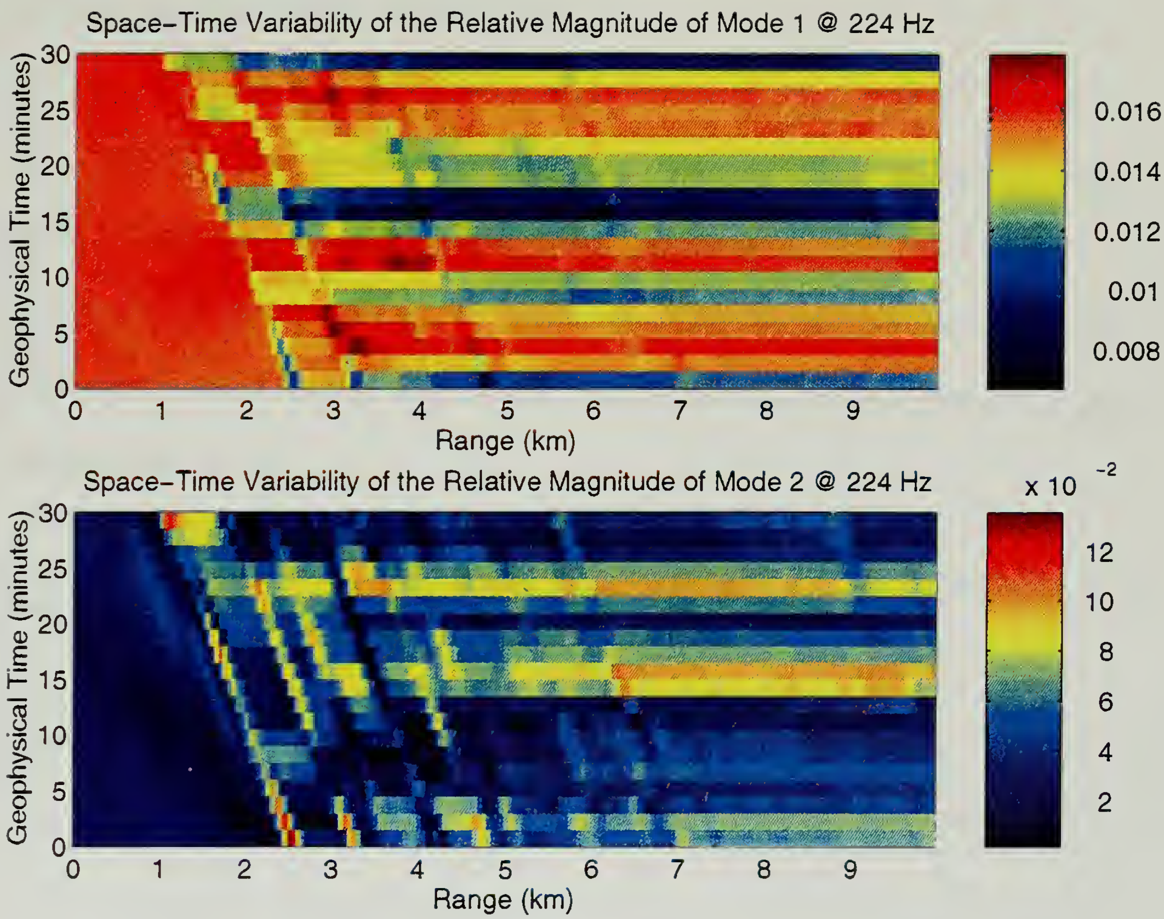

Figure 9. Space-time variability of the relative magnitudes of mode 1 (top) and mode 2 (bottom).

B. CORRELATION OF SOUND PRESSURE IN DEPTH

To investigate the correlation of the sound pressure field in depth, 7 phones representing a vertical line array (VLA) are synthesized at 10 km from the CW sound source. The first phone is located at the 10 m depth and the 7th phone at the 70 m depth. These phones are labelled as phone number 1 to 7 from top to bottom. The depth spacing between each phone is 10 m.

Table 3.1 shows the auto and cross-correlation coefficients (at zero lag) of the complex sound pressure perturbation time series at different phones. For all the cross-correlation functions computed, it is observed that the peak occurs at zero lag. This indicates that the sound field is dominated by the low modes or the low grazing-angle acoustic energy.

Table 3.1 Cross-correlation coefficients of the sound pressure perturbation time series at the various phones of a VLA.

Phone #	1	2	3	4	5	6	7
1	1	0.9310	0.9061	0.9296	0.8934	0.7599	0.8745
2	0.9310	1	0.8432	0.8535	0.8276	0.6765	0.8387
3	0.9061	0.8432	1	0.9385	0.9773	0.8229	0.9679
4	0.9296	0.8535	0.9385	1	0.9558	0.8277	0.9030
5	0.8934	0.8276	0.9773	0.9558	1	0.8436	0.9730
6	0.7599	0.6765	0.8229	0.8277	0.8436	1	0.7720
7	0.8745	0.8387	0.9679	0.9030	0.9730	0.7720	1

High correlations of the sound pressure perturbations over the entire VLA (or the entire water depth) are obtained. This outcome is expected because the large-amplitude soliton affects a major portion of the shallow-water column producing sound speed fluctuations that are in phase at all depths.

Table 3.2 shows the de-correlation times estimated from the auto-correlation functions of the sound pressure perturbation time series at various phones. The de-correlation time is taken to be the lag at which the correlation coefficient drops to a value of 0.3679, i.e., e^{-1}. A de-correlation time of 50-60 seconds is found at all the phones. The sound pressure perturbations in all the phones in the VLA are likely to have similar structure due again to a shallow water depth and the large-amplitude and vertically in-phase sound speed changes. The estimated de-correlation times indicate that the integration time for coherent processing for any 224-Hz omnidirectional receiver system should be in the order of one minute when the soliton packets are present. Within the one minute interval, sound pressure will be coherent. Beyond which it will become incoherent.

Table 3.2 De-correlation times of the sound pressure perturbation time series at various phones.

Phone #	1	2	3	4	5	6	7
De-correlation time(s)	60	60	50	55	50	55	55

C. CORRELATION OF MODAL AMPLITUDE

The auto and cross correlations between the modal amplitudes of the first five modes at zero lag and a range of 10 km from the sound source are shown in table 3.3. There is only moderate corss correlation between mode 1 and mode 2 as well as between mode 1 and mode 3. The generally low cross-correlation between the modal amplitude perturbations of the different modes suggest that the phase fluctuations cumulated over a distance of 10 km are dissimilar for different modes.

Table 3.3 Auto-correlation and cross-correlation coefficients of the modal amplitude perturbation time series

Mode #	1	2	3	4	5
1	1	0.5891	0.5713	0.2602	0.3974
2	0.5891	1	0.3402	0.1102	0.2370
3	0.5713	0.3402	1	0.3012	0.2120
4	0.2602	0.1102	0.3012	1	0.2331
5	0.3974	0.2370	0.2120	0.2331	1

The de-correlation times of the various modes is tabulated in table 3.4. A value of 0.3679 is again used to determine the de-correlation time. There are considerable variability in the de-correlation times of the various modes. Mode 1 has the highest de-correlation time. Given a negative sound speed profile in the SWARM's site (see figure 6), the effects of the wave packet on mode 1 may be minimum because the vertical span of mode 1 could be well below the depths of maximal sound speed perturbation induced by the soliton packet. Due to the larger vertical spans of the higher modes, they are likely to be affected more by the soliton wave packet. The modal amplitudes are obtainable by modal beamforming using a VLA . Since the de-correlation times of the modal amplitudes are longer than the sound pressure observed by a single phone, the use of VLAs in shallow water can be more advantageous. A shorter de-correlation time in the single-phone measurements is due to the interference of the multimodes.

Table 3.4 De-correlation time of the amplitudes of various modes.

Mode #	1	2	3	4	5
De-correlation time(s)	300	75	112	90	83

IV. CONCLUSIONS

A soliton wave packet was extracted from the data collected by the ADCPs deployed in SWARM '95 over the Mid-Atlantic Bight. Using the approximation that the packet retains its shape and moves at a uniform speed over a short duration of time (say 30 minutes), perturbed sound speed as a function of space and time was synthesized. Acoustic simulation by placing a 224-Hz CW sound source at a depth of 50 m and a 7-element, 10-m spacing vertical line array receiver located 10 km away was then carried out. Using the synthesized sound-speed field as input to the coupled normal-mode model of Chiu et al. (1996), the sound pressure field as well as the modal amplitudes were calculated. Once these acoustic quantities were obtained, the correlation between sound pressure at different depths and between modal amplitudes were computed from which the acoustic de-correlation times and lengths of these quantities were examined.

From the investigations carried out thus far, the following conclusions can be made:

1. It is observed that the modal magnitudes change abruptly at the leading edge of the soliton packet as the packet propagates toward the sound source. Coupling between the modes takes place immediately after their initial contact with the packet. It is also observed that active coupling only occurs within the front portion (approximately the first half) of the wave packet where the perturbations are large. At

the downstream of the packet, the coupling of modes is significantly lessened. The time scale of the variability of both the modal magnitudes as well as transmission loss is approximately 10 minutes.

2. There is high correlation between sound pressure at different depths. This outcome is expected because the large-amplitude soliton affect a major portion of the shallow-water column producing sound speed fluctuations that are in phase at all depths. The de-correlation times of sound pressure at all the phones are approximately the same. They are about one minute, independent of depth.

3. There are large variability in the de-correlation times of various modes. Mode 1 has the highest de-correlation time of about 300 seconds, indicating possible less variability suffered by this mode compared with other modes. The higher modes have de-correlation times in the order of 100 seconds. With a negative sound speed profile in the SWARM site, the effects of the soliton wave packet on mode 1 may be minimum because the vertical span of mode 1 could be well below the depths of maximal sound speed perturbation. Higher modes are likely to be affected more by the soliton wave packet due to their larger vertical spans.

To further investigate the effects of internal soliton wave packets on the acoustic wavefield on a continental shelf over a longer period, it will be necessary to use numerical solutions to the modified KdV equation developed by Liu (1988). This will enable modeling the life time of a soliton packet instead of limiting it to less than 30 minutes as constrained by the form-preserving, uniform-speed approximation. With this more comprehensive modeling method for the sound speed changes, the approach outlined in this thesis can then be used to calculate sound pressure, modal amplitudes and their de-correlation times and lengths for various SWARM '95 transmission configurations and frequencies. The simulated results can then be compared and validated with the data obtained by the vertical arrays deployed in SWARM '95. This will definitely lead to a better understanding of the acoustic influences by soliton wave packets and provide an insight into sonar system performance and design in shallow waters where large amplitude internal soliton wave packets are present.

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